INTEGRATED ULTRASONIC TECHNIQUE FOR CHARACTERIZATION OF COMPOSITE MATERIALS

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INTRODUCTION

The comprehensive non-destructive evaluation of modern composite materials requires the application of complementary techniques for the characterization of fabricated laminates. Current measurement methods, such as velocity and attenuation measurements of ultrasonic waves are, however, not integrated but require different ultrasonic and electronic system configurations.

In this paper, an ultrasonic technique, previously developed by the authors for simultaneous wave speed and attenuation measurements [1], is applied to characterize composites. The amplitudes of tone-burst signals generated over a selected frequency range were measured to determine attenuation. For the determination of the wave velocity , a number of frequencies are selected at which a zero crossing of the tone-burst signal coincides with a zero crossing of a continuous reference sine wave. Various configurations of ultrasonic transducers for integrated measurements have also been investigated.

A selected configuration of the ultrasonic and electronic system has been applied to characterize the porosity content in 200-ply unidirectional graphite/epoxy composite laminates.

ULTRASONIC CONFIGURATION FOR MEASUREMENTS

The attenuation and velocity of ultrasonic waves can be measured by using pulse-echo or through-transmission techniques. For materials with low signal loss, the information on absolute values of wave velocity and attenuation can be obtained by using multiple echoes from the bottom of the specimen. However, for materials with high porosity, one may not obtain even a single echo from the back face of the specimen due to signal loss. The use of non-contact transducers which is desirable for industrial purposes makes this problem even more difficult.

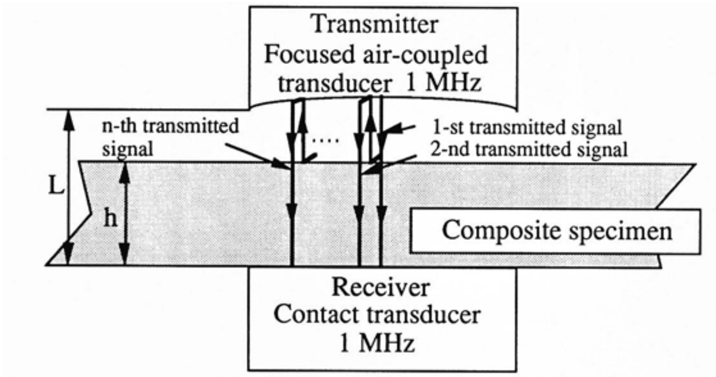

Fig. 1. Schematic of signal propagation.

In the work presented only transmitted signals were used for the measurements. Two techniques have been used to utilize the same ultrasonic transducer configuration for integrated velocity and attenuation measurements.

For velocity measurements an ultrasonic technique using multiple transmitted signals has been developed. A schematic of the signal propagation is shown in Fig. 1. The air-coupled transmitter generates an ultrasonic wave which, being repeatedly reflected by the front face of the specimen and the face of the transmitter provides a train of signals that is received by the contact transducer on the opposite side of the specimen. Figure 2 shows a train of six signals. The time-of flight for the directly transmitted signal (#1) can be expressed as

$$t_1 = \frac{L-h}{c_0} + \frac{h}{c} \tag{1}$$

where t_1 = time-of-flight of directly transmitted signal,
L = distance between transmitter and receiver,
h = thickness of the composite specimen,
c_0 = velocity of ultrasonic wave in air,
c = velocity of ultrasonic wave in the composite.

For the second and the n^{th} transmitted signals we can write, respectively

$$t_2 = \frac{3(L-h)}{c_0} + \frac{h}{c} \tag{2}$$

$$t_n = \frac{(2n-1)\cdot(L-h)}{c_0} + \frac{h}{c} \tag{3}$$

where t_2 = time-of-flight of the second transmitted signal,
t_n = time-of-flight of the n^{th} transmitted signal.

The velocity of longitudinal waves in the composite can be determined from Eq. (3) as

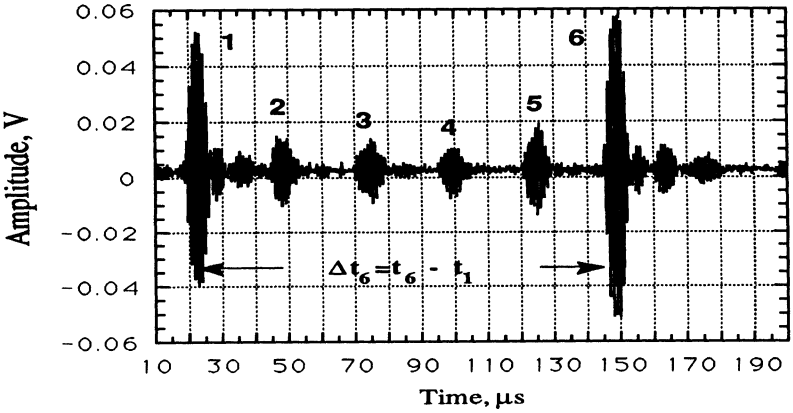

Fig. 2. Waveforms of transmitted signals.

$$c = \frac{c_0 \cdot h}{t_n \cdot c_0 - (2n-1) \cdot (L-h)} \qquad (4)$$

For composite laminates of variable thickness it is of great importance to obtain information on the wave speed at different locations on the specimen surface without additional measurements of the thickness at each point. In this case it was suggested to use multiple signals transmitted through the composite in conjunction with direct transmission from transmitter to receiver through the air gap without a composite specimen between transducers.

The time-of-flight for direct air transmission can be expressed as

$$t_0 = \frac{L}{c_0} \qquad (5)$$

where t_0 = time -of-flight for the signal transmitted through the air.

For the time delays between different signals transmitted from transmitter to receiver we can write

$$\Delta t_0 = t_0 - t_1 = h \cdot \left(\frac{1}{c_0} - \frac{1}{c}\right) \qquad (6)$$

$$\Delta t_n = t_n - t_1 = \frac{2(n-1) \cdot (L-h)}{c_0} \qquad (7)$$

where Δt_0 = time delay between signal propagation from transmitter to receiver without composite specimen (t_0) and with composite specimen between transducers(t_1), Δt_n = time delay between the n_{th} and the first signals transmitted through composite. Substitution of Eqs. (6) and (7) in Eq. (3) gives us

$$c = \frac{c_0\left[L - \frac{c_0 \Delta t_n}{2(n-1)}\right]}{L - \frac{c_0 \Delta t_n}{2(n-1)} - c_0 \Delta t_0} \qquad (8)$$

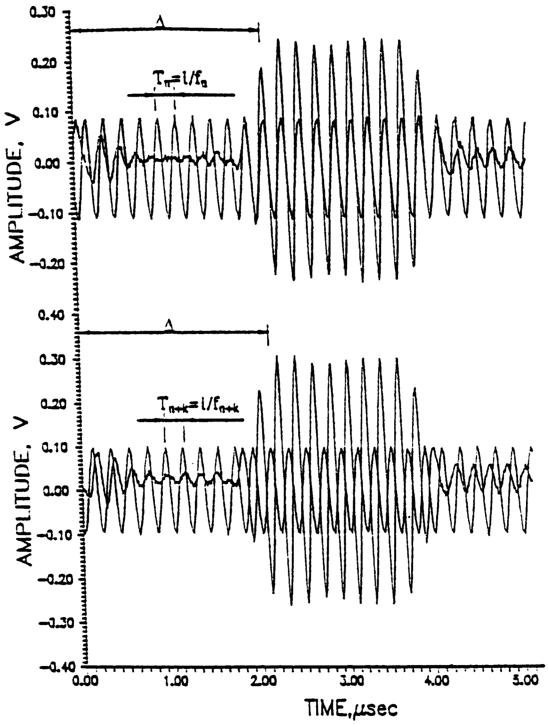

Fig. 3. Timing diagram for time-of-flight measurement.

Using Eq. (8) the absolute velocity of an ultrasonic wave in the composite can be found independently of the thickness of the composite laminate.

To determine time delays Δt_n and Δt_0 the times-of-flight of the three signals transmitted from transmitter to receiver have to be measured. The timing diagram for the time-of-flight measurement is shown in Fig. 3. To measure the time-of-flight simultaneously with signal amplitude the frequency of the source signal is adjusted so that for each recorded signal (one at the time) a zero-crossing coincides with a zero-crossing of the reference sine wave. Then the frequency is varied until the next coincidence of zero-crossing occurs. This process can be repeated, say k times, and in this manner k neighboring frequencies will be selected. The phase conditions for coincidence of zero-crossings at these frequencies are

$$\Delta\varphi_n = 2\pi \cdot f_n \cdot \Delta = 2\pi n \qquad (9)$$

$$\Delta\varphi_{n+k} = 2\pi \cdot f_{n+k} \cdot \Delta = 2\pi(n+\frac{k}{2}) \qquad (10)$$

where Δ = time-of-flight of the signal.

By subtracting Eqs. (9) and (10) we find

$$\Delta = \frac{k}{2(f_{n+k}-f_n)} \qquad (11)$$

After the times-of-flight for all the signals have been measured, the wave velocity can be obtained from Eq. (8) for known c_0 and L.

To measure the attenuation the indirect (or relative) method described in [2] was used. In this case the relative response function η of the composite specimen can be measured with respect to the response function at a selected location on the specimen surface taken as the reference

$$\eta = \frac{D_C}{D_{Cref}} \tag{12}$$

where D_C=response function for transmission through composite specimen at sample point, D_{Cref}=response function for transmission through composite at reference location on the specimen surface.

To determine the relative response function η the signals directly transmitted through the composite specimen are to be measured for both sample and reference locations. These signals can be expressed as

$$V_s = A_T \cdot D_{As} \cdot T_{1s} \cdot D_{Cs} \cdot T_{2s} \cdot S \tag{13}$$

$$V_{ref} = A_T \cdot D_{Aref} \cdot T_{1ref} \cdot D_{Cref} \cdot T_{2ref} \cdot S \tag{14}$$

where V_s and V_{ref} = amplitudes of the signals transmitted from transmitter to receiver at sample and reference locations, respectively,
A_T = response function of the transmitter,
D_{As} and D_{Aref} = response functions for transmission through the air at sample and reference locations, respectively,
T_{1s} and T_{1ref} = coefficients for transmission through air-composite interface at sample and reference locations, respectively.
D_{Cs} and D_{Cref} = response functions for transmission through composite at sample and reference locations, respectively,
T_{2s} and T_{2ref} = coefficients for transmission through composite-receiver interface at sample and reference locations, respectively,
S = response function of the receiver.

Assuming uniform conditions of the specimen surface and taking into consideration that

$$D_{As} = e^{\alpha_A \cdot (L-h_{Cs})} \tag{15}$$

$$D_{Aref} = e^{\alpha_A \cdot (L-h_{Cref})} \tag{16}$$

where α_A = attenuation coefficient for the air, we can write for the relative response function in terms of the transmitted signals

$$\eta = \frac{V_s}{V_{ref}} e^{\alpha_A(h_{Cs}-h_{Cref})} \tag{17}$$

Then the absolute attenuation coefficient of the specimen at the sample location can be determined as

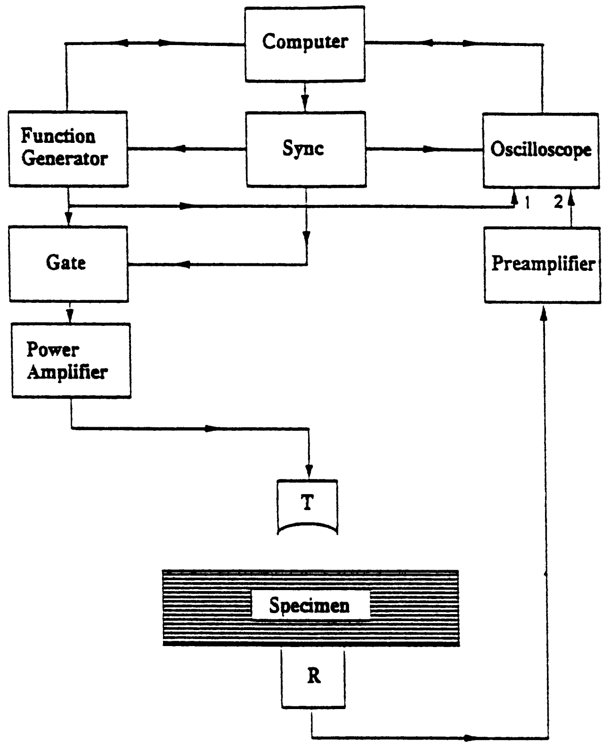

Fig. 4. Schematic of the experiment.

$$\alpha_{Cs} = \frac{h_{Cref}}{h_{Cs}} \cdot \alpha_{Cref} - \alpha_A \cdot \left(\frac{h_{Cref}}{h_{Cs}} - 1\right) + \frac{20}{h_{Cs}} \lg\frac{V_{Cs}}{V_{Cref}} \qquad (18)$$

where α_{Cref} = absolute attenuation coefficient of the composite at the reference location where direct attenuation measurement is possible.

The thickness of the composite specimen at any location can be obtained from Eq.(6) as

$$h = L - \frac{\Delta t_n \cdot c_0}{2 \cdot (n-1)} \qquad (19)$$

EXPERIMENTAL PROCEDURE

A schematic of the electronic system used in the experiments is shown in Fig. 4. An HP3325B function generator produces a continuous sine wave signal under control of a desktop computer. This signal is applied as a reference signal to channel 1 of an oscilloscope (Tek 2465B) and to the Metrotek MG701GATE. The latter produces a tone-burst of the desired number of cycles with peak-to-peak voltage of 0.25V. The tone-burst is amplified by a 50DB power amplifier (ENI radio frequency 325LA) to a 75V peak-to-peak voltage. The amplified tone-burst is subsequently applied to the focused air-coupled transducer (Ultran KG75-1-P2) with central frequency 1.0 MHz and focal length 2.0". The transducer sends an ultrasonic wave through the air gap toward the composite specimen. The wave is

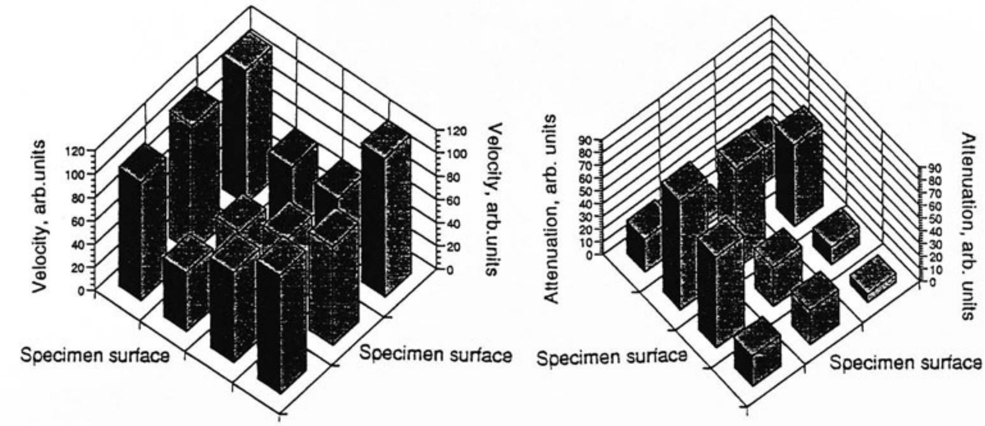

Fig. 5. Velocity and attenuation of longitudinal waves at different locations on the specimen surface.

transmitted through the air-composite interface as shown in Fig. 1. The signal received by the contact receiver (Panametrics V103 1.0 MHz) is amplified by a 5662 Panametrics preamplifier. The output waveform is then applied to the channel 2 of the oscilloscope and acquired by the computer. As the frequency is varied under computer control, data points from the measured signal waveforms are compared with data points from the reference sine wave. The frequencies at which coincidences of zero-crossings occur are automatically selected and the wave velocity is determined using Eqs. (6)-(8) and (11) along with the signal amplitude. It was experimentally found by the authors that selected signals transmitted through the composite (signal #6 in Fig. 2) have much higher amplitude. This phenomenon which makes it possible to increase accuracy of velocity and attenuation measurements has been investigated in some detail in Ref. [3].

EXAMPLE: NDE OF A GRAPHITE/EPOXY COMPOSITE

As an application of the technique, an investigation of the porosity using velocity and attenuation measurements was carried out for an unidirectional 200-ply graphite/epoxy composite laminate(AS4/3501-6). Absolute velocity and relative attenuation of longitudinal waves were measured at various locations on the specimen surface. Figure 5 shows the data obtained from the measurements. Following velocity and attenuation measurements, polished cross-sections of selected parts of the specimen were examined under the optical microscope. Void content was measured for each location and the results were compared with ultrasonic measurements. A qualitative correlation between wave velocity, attenuation and porosity is shown in Fig. 6. Scattering of the results at very low void content can be explained by difficulties of the microscopic measurement of porosity in this range of void content. On the other hand results obtained for higher void content (about 1%) show a consistent trend of respectively decreasing velocity and increasing attenuation with increasing void content in the composite material.

CONCLUSION

An integrated ultrasonic technique using an air-coupled focused transducer has been developed for simultaneous wave velocity and attenuation measurements in highly attenuative materials of variable thickness. The technique makes it possible to obtain data

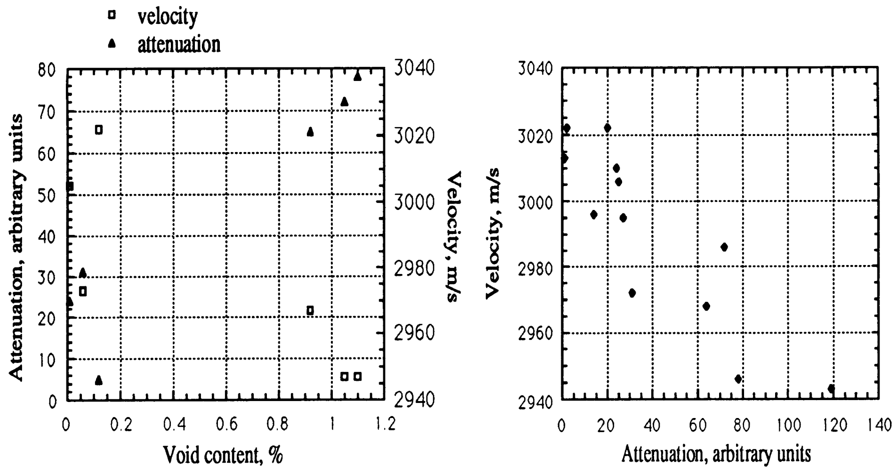

Fig. 6. Correlation between velocity, attenuation, and void content in 200-ply composite specimen.

on absolute velocity and attenuation in the material without additional measurements of the material thickness at different locations on the specimen surface.

The developed technique was applied to characterize porosity in a 200-ply unidirectional graphite/epoxy composite laminate. Velocity and attenuation measurements were correlated with porosity measurements by microscopic analysis at various locations on the surface of the composite specimen.

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